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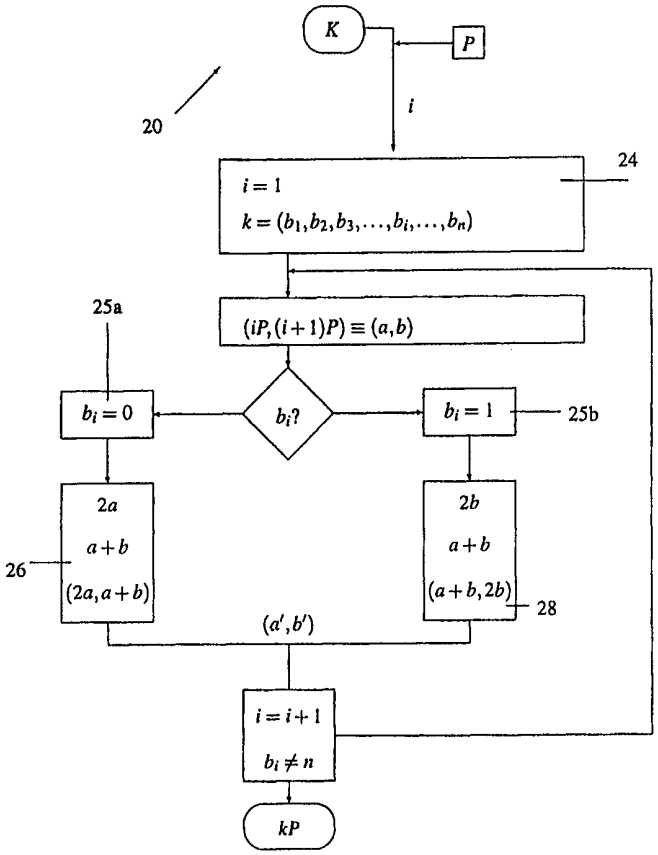
(54) Title: POWER SIGNATURE ATTACK RESISTANT CRYPTOGRAPHY

(57) Abstract

This invention provides a method of computing a multiple k of a point P on an elliptic curve defined over a field, the method including the steps of representing the number k as binary vector k_I, forming an ordered pair of point P_1 and P_2, wherein the points P_1 and P_2 differ at most by P, and selecting each of the bits k_i in sequence, and for each of the k_i, upon k_i being a 0, computing a new set of points P_1', P_2' by doubling the first point P_1 to generate the point P_1' and adding the points P_1 and P_2 to generate the point P_2' or upon k_i being a 1, computing a new set of points P_1', P_2' by doubling the second point P_2 to generate the point P_2' and adding the points P_1 and P_2 to produce the point P_1', whereby the doubles or adds are always performed in the same order for each of the bits b_i, thereby minimizing a timing attack on the method. An embodiment of the invention applies to both multiplicative and additive groups.



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POWER SIGNATURE ATTACK RESISTANT CRYPTOGRAPHY

This invention relates to a method and apparatus for minimizing power signature attacks in cryptographic systems.

BACKGROUND OF THE INVENTION

Cryptographic systems generally owe their security to the fact that a particular piece of information is kept secret without which it is almost impossible to break the scheme. The secret information must generally be stored within a secure boundary in the cryptographic processor, making it difficult for an attacker to get at it directly. However, various schemes or attacks have been attempted in order to obtain this secret information. One of these is the timing or power signature attack.

The timing attack (or "side channel attack") is an obvious result of sequential computational operations performed during cryptographic operations. The attack usually exploits some implementation aspect of a cryptographic algorithm.

For example current public key cryptographic schemes such as RSA and elliptic curve (EC) operate over mathematical groups; Z_n^* ($n=pq$) in RSA, discrete log systems in a finite field F^*_q (q is a power of a prime), $F^*_{2^M}$ or an EC group over these finite fields. The group operations, called multiplication modulo n, in RSA, and addition of points in EC are sequentially repeated in a particular way to perform a scalar operation. In RSA the operand is called an exponent, the operation is called exponentiation and the method of multiplying is commonly known as repeated square-and-multiply. Thus given a number $a \in Z_n^*$ and an integer $0 \leq k < p$, the exponent, whose binary representation is $k = \sum_{i=0}^{t} k_i 2^i$ a value a^k mod n may be calculated by repeated use of the "square-and-multiply" algorithm (described in Handbook of Applied Cryptography P.615). Similarly given $g(x) \in F_p m$ and an integer $0 \leq k \leq p^m - 1$ then $g(x)^k$ mod $f(x)$ may be calculated by this method.

On the other hand, in EC the operand is a scalar multiplier, the operation is called scalar multiplication of a point, and the method is known as "double-and-add". Thus if k is a positive integer and P is an elliptic curve point then kP may be obtained by the "double-and-add" method. Both these methods are well known in the art and will not be discussed further.

As mentioned earlier, an attacker once in possession of the private key (either long term or session) is able to forge signatures and decrypt secret messages for the attacked entity. Thus it is paramount to maintain the secrecy or integrity of the private key in the system.

Many techniques have been suggested to obtain the private key. The encryption operations are performed either in a special purpose or general-purpose processor operating in a sequential manner. Recent attack methods have been proposed in open literature as for example described in Paul Kochers's article "Timing attacks on implementations of Diffie-Hellman, RSA, DSS and other systems". These attacks have been based on timing analysis of these processors or in other words timing analysis of 'black box' operations. In one instance an attacker by capturing the instantaneous power usage of a processor throughout a private key operation obtains a power signature. The power signature relates to the number of gates operating at each clock cycle. Each fundamental operation as described in the preceding paragraph generates a distinct timing pattern. Other methods exist for obtaining a power signature than instantaneous power usage.

Laborious but careful analysis of an end-to-end waveform can decompose the order of add-and-double or square-and-multiply operations. Using the standard algorithm, either a double or square must occur for each bit of either the exponent or scalar multiplier respectively. Therefore, the places where double waveforms are adjacent each other represent bit positions with zeros and places where there are add waveforms indicate bits with ones. Thus, these timing measurements can be analyzed to find the entire secret key and thus compromise the system.

In addition to the "square and multiply" or "double and add" techniques mentioned earlier, other methods to compute kP are for example the "binary ladder" or Montgomery method described in "Speeding the Pollard and Elliptic Curve Methods of Factorization" by Peter L. Montgomery. In this method the x-coordinates of the pair of points (iP, (i+1)P) are computed. The Montgomery method is an efficient algorithm for performing modula multiplication, more clearly illustrated by an example. Given a group $E(F_p)$ and given a point P on the elliptic curve, the Montgomery method may be used to compute another point kP. Given an ordered pair of points $(iP, (i + 1)P)$, then for each of the bits of the binary representation of k, if bit i is a 0 then the next set of points computed is $(2iP, (2i + 1)P)$ and if bit i is 1, then the next set of points is $((2i + 1)P, (2i + 2)P)$, that is, the first of the pair is derived from a doubling or an adding depending on whether the bit is a 0 or 1.

In a processor, each of the doubles and adds involve multiple operations which generate unique power signatures. By observing these power signatures as shown schematically in figure 1(a), the attacker may derive a sequence of 0s and 1s and thus, the scalar or exponent being used.

The Montgomery method is preferable in EC cryptographic systems because of its extreme efficiency over the straight "double and add" described earlier.

The attack on the Montgomery method as described above is particularly important if performing RSA private key operations. In a recent paper published by Dan Boneh et al entitled "An Attack On RSA Given A Small Fraction Of The Private Key Bits", it has been shown that for RSA with a low public exponent, given a quarter of the bits of the private key, an adversary can determine the entire private key. With this attack combined with the power signature attack described above, the RSA scheme is extremely vulnerable.

Thus, it is an object of this invention to provide a system which minimizes the risk of a successful timing attack particularly when utilizing the Montgomery method on private key operations.

SUMMARY OF THE INVENTION

In accordance with this invention, there is provided a method of computing a multiple k of a point P on an elliptic curve defined over a field, said method comprising the steps of:

a) representing the number k as binary vector of bits k_i ;

b) forming an ordered pair of points P_1 and P_2, wherein the points P_1 and P_2 differ at most by P; and

c) selecting each said bits k_i in sequence; and for each of said k_i ;

i) upon k_i being a 0

ii) computing a new set of points P_1', P_2' by doubling the first point P_1 to generate said point P_1'; and

iii) adding the points P_1 and P_2 to generate the point P_2' ;

or upon k_i being a 1

iv) computing a new set of points P_1', P_2' by doubling the second point P_2 to generate the point P_2'; and

v) adding the points P_1 and P_2 to produce the point P_1',

whereby said doubles or adds are always performed in the same order for each of said bits b_i, thereby minimizing a timing attack on said method.

In accordance with a further aspect of this invention, the field is either F_2^m or F_p.

In accordance with a further aspect of this invention, there is provided a processor hardware for implementing the method.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the preferred embodiments of the invention will become more apparent in the following detailed description in which reference is made to the appended drawings wherein:

Figures 1 (a) and (b) is a schematic representation of a processor power usage signature;

Figure 2 is a flow diagram of a method according to an embodiment of the present invention;

Figure 3 is a schematic diagram of a symmetric processor implementing a method according to an embodiment of the present invention; and

Figure 4 is a schematic representation of an integer k in binary.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to figure 2, a generalized algorithm for computing a multiple of a point on an elliptic curve defined over a field F_2^m or F_P is indicated generally by numeral 20. In this embodiment, the point P is a parameter of the system. The algorithm computes a multiple of the point kP, wherein the scalar k is possibly a private key or other secret value. The scalar k is represented in a register as a binary vector having bits b_I 24. A pair of elements (a,b) is created, where a and b are points on an elliptic curve which differ at most by P or in the case of the group F_p, a and b are elements g which differ by a multiple g.

In the present embodiment, we will consider an elliptic curve scheme thus, the elements a and b correspond to the x-coordinates of an ordered pair of points iP and $(i + 1P)$. An improved Montgomery method for deriving and utilising the x-coordinates of elliptic curve points is described in the applicants pending US patent application serial No. 09/047,518, incorporated herein by reference. A bit b_i beginning with the first bit of the binary representation of the scalar k is evaluated. Depending on the value of the bit, one of two algorithms 26 or 28 are chosen. If the bit is a 0 shown at block 25a, the first element a of the input pair (a,b) is doubled and stored in the first element a of the output pair (a',b'). While the first and second elements of the input are added $a + b$ and placed in the second

element *b'* of the output pair *(a',b')*. If the bit is a 1, shown at block 25b, he second element b of the input pair *(a,b)* is doubled and stored in the second element b at the output pair *(a',b')*, while the first and second input elements are added, i.e., a+b, and placed in the first element *a'* of the output pair *(a',b')*,. These steps are repeated for all bits of the scalar *k*.

It may be seen thus, from figure 1(b), that performing the "double" operation followed by the "add" operation for each of the bits, produces a consistent power signature waveform, thus providing little information to a potential attacker. The operations could also be performed in reverse order, i.e., first performing the "add" then the "double" operation. In an RSA scheme, the analogous operations are "square and multiply".

More clearly, suppose we are computing kP using the "binary ladder" method, then after some iterations we have the x-coordinates of (iP,(i+1)P), i.e. having processed i bits of k as shown schematically in figure 4. If the next bit to be processed is 0, then we must construct the (ordered pair of) x-coordinates (2iP,(2i+1P)P). If the next bi+b is 1, then we must produce the (ordered pair of) x-coordinates ((2i+1)P, (2i+2)P).

It is likely that the "double" formula requires roughly the same amount of power (and time) regardless of the input. It is likely that add formulas require roughly the same amount of power (and time) regardless of the input. However, an execution of the double formula will require a different amount (less, if the usual Montgomery formulas are used) of power than an execution of the add formula.

Hence, by monitoring the power bar, we can distinguish between a "double" and an "add". Thus, if these equations are executed in a consistent order, then the power signatures of a 1 being processed or a 0 being processed are indistinguishable. Each consists of a "double" power signature, followed by an "add" power signature.

We mention that if the order of evaluation is reversed in both cases, then the power signatures are still indistinguishable.

Hence, this method for computing kP on an elliptic curve is preferred since it avoids revealing the integer k through power consumption statistics. When the "Montgomery" "double" and "add" formulas are used, this method is also efficient, especially when the projective form is used which avoids inversions.

In the context of efficiencies, it is noted that at each step of the "Binary ladder" method, two independent operations must be performed. That is, the results of the "add" formula are not needed for the "double" formula and vice versa. This allows for an efficient parallel hardware implementation.

Thus, referring to figure 3, a schematic parallel hardware implementation of the present method is shown by numeral 30. In this implementation, a first and second special purpose processor is provided. The first processor 32 performs either a "double" or "square or both operations, while the second processor 34 performs a "add" or "multiply" or both operations. A main processor 36 determines which of the special processor 32 and 34 are activated.

Each processor 32 and 34 are driven simultaneously. (The circuits may take different times to execute, however). The inputs and outputs of these circuits are dealt with in accordance with the case we are in, i.e., with bit $b_i=0$ or with bit $b_i=1$. This simple instance gives a speed up of almost a factor 2 over a serial implementation. Note that at least in the case of the traditional projective Montgomery formulae, the add circuit takes longer and is more complicated than the double circuit. Since there is no need to have the double circuit finish sooner than the add circuit, it can be slower. In practice, this might mean that the double circuit can be built more cheaply.

Although the invention has been described with reference to certain specific embodiments, various modifications thereof will be apparent to those skilled in the art without departing from the spirit and scope of the invention as outlined in the claims appended hereto.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of computing a multiple k of a point P on an elliptic curve defined over a field, said method comprising the steps of:

a) representing the number k as binary vector k_i ;

b) forming an ordered pair of points P_1 and P_2, wherein the points P_1 and P_2 differ at most by P; and

c) selecting each said bits k_i in sequence; and for each of said k_i ;

i) upon k_i being a 0, computing a new set of points P_1', P_2' by doubling the first point P_1 to generate said point P_1'; and adding the points P_1 and P_2 to generate the point P_2' ;

or

ii) upon k_i being a 1, computing a new set of points P_1', P_2' by doubling the second point P_2 to generate the point P_2'; and adding the points P_1 and P_2 to produce the point P_1',

whereby said doubles or adds are always performed in the same order for each of said bits b_i, thereby minimizing a timing attack on said method.

2. A method as defined in claim 1, said field being defined over F_2^m.

3. A method as defined in claim 1, said field being defined over F_p.

Figure 1.

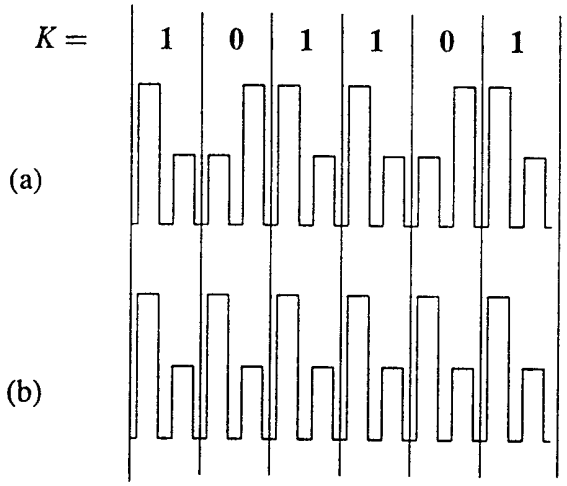


Figure 2.

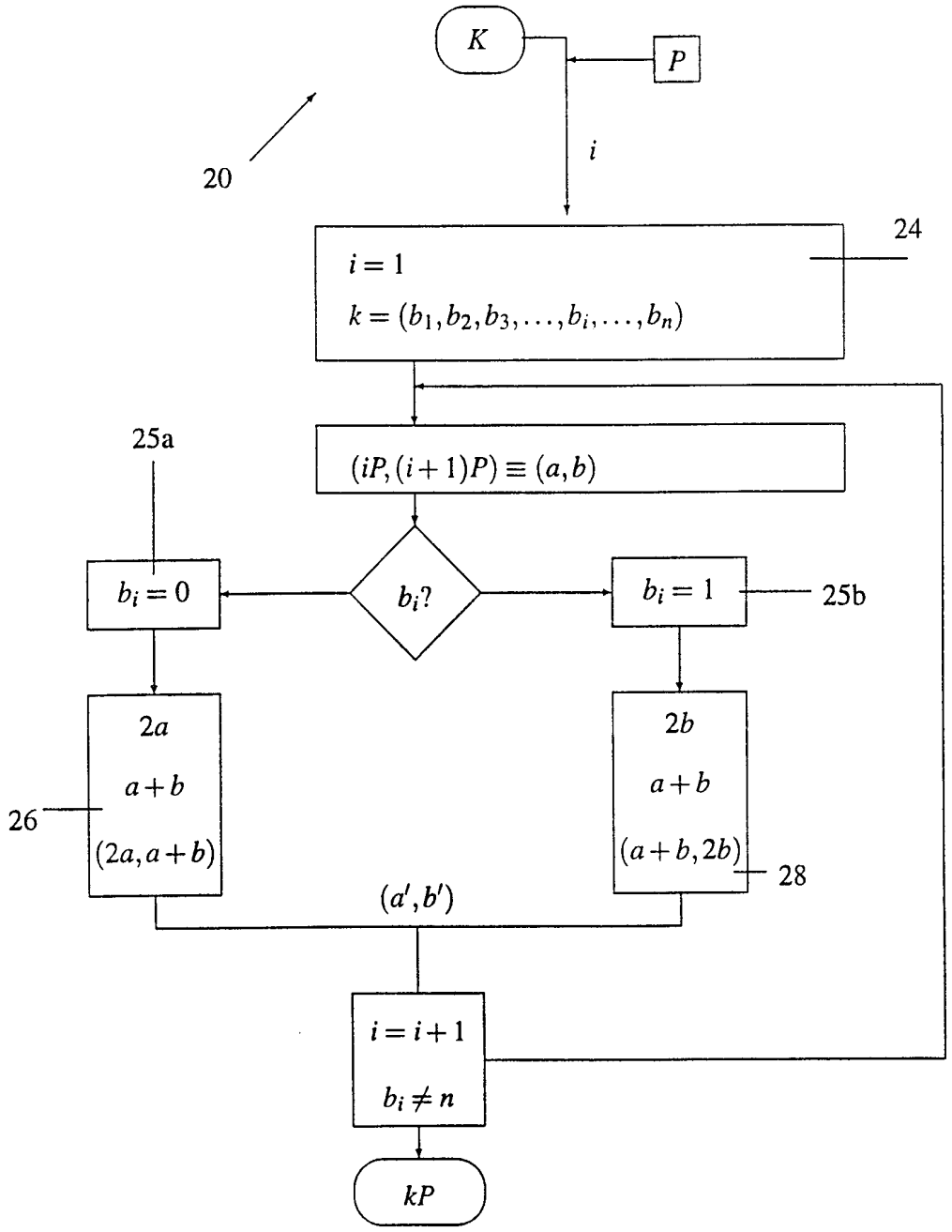

K
P
i
20
24
$i = 1$
$k = (b_1, b_2, b_3, \ldots, b_i, \ldots, b_n)$
25a
$(iP, (i+1)P) \equiv (a, b)$
$b_i = 0$
b_i?
$b_i = 1$
25b
2a
$a + b$
$(2a, a + b)$
26
2b
$a + b$
$(a + b, 2b)$
28
(a', b')
$i = i + 1$
$b_i \neq n$
kP

Figure 3.

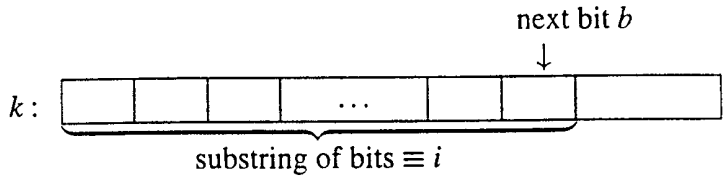
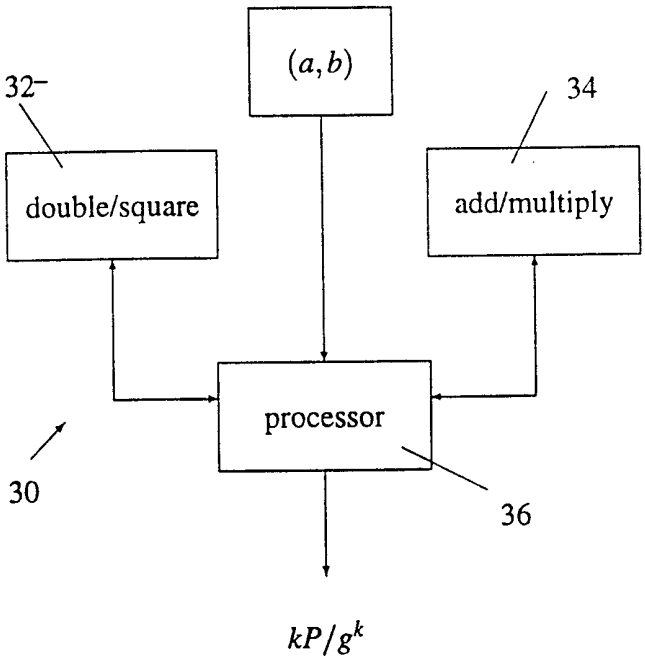


Figure 4.



INTERNATIONAL SEARCH REPORT

Inter nal Application No
PCT/CA 99/00919

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G06F7/72

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	AGNEW G B ET AL: "AN IMPLEMENTATION OF ELLIPTIC CURVE CRYPTOSYSTEMS OVER F2155" IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, vol. 11, no. 5, page 804-813 XP000399849 IEEE INC. NEW YORK ISSN: 0733-8716 page 808, right-hand column, line 23 - line 26 --- -/--	1-3

[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
6 January 2000	21/01/2000

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Inter nal Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	KOCHER P C: "Timing attacks on implementations of Diffie-Hellman, RSA, DSS, and other systems" ADVANCES IN CRYPTOLOGY - CRYPTO'96. 16TH ANNUAL INTERNATIONAL CRYPTOLOGY CONFERENCE. PROCEEDINGS, ADVANCES IN CRYPTOLOGY - CRYPTO '96, SANTA BARBARA, CA, USA, 18-22 AUG. 1996, pages 104-113, XP000626590 1996, Berlin, Germany, Springer-Verlag, Germany ISBN: 3-540-61512-1 cited in the application section 9 -----	1-3

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